Photocatalytic Systems

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Microplastic pollution has become a global environmental concern with detrimental effects on ecosystems and human health. Effective removal of microplastics from water sources is crucial to mitigate their impacts. Advanced oxidative processes (AOPs) have emerged as promising strategies for the degradation and elimination of microplastics.

microplastics removal advanced oxidation processes photocatalysis

1. Introduction

Photocatalysis involves the use of a catalyst, typically a semiconductor material, to accelerate a chemical reaction in the presence of light. For MP degradation, the photocatalyst is typically employed to generate reactive oxygen species (ROS) upon exposure to light. These ROS, such as hydroxyl radicals (OH·), possess high reactivity and can break down the chemical bonds in microplastics, leading to their degradation. Titanium dioxide (TiO_2) and zinc oxide (ZnO) are the most commonly used photocatalysts in microplastic degradation studies. Both semiconductors have an appropriate bandgap, 3.2 eV for TiO_2 and 3.4 eV for ZnO [1], which, upon light interaction, leads to the generation of various reactive species. When semiconductors are excited by light with energy higher than the bandgap, charge separation occurs, resulting in the release of free electrons that transition from the valence band to the conduction band. Several significant reactive species are formed during the interaction with light. Consequently, photoexcitation creates a “hole” in the valence band of the semiconductor. When photocatalysts are illuminated with ultraviolet (UV) light, they can generate ROS, which reacts with the microplastic surface and initiate degradation processes.

It has been reported that several factors affect the photocatalytic degradation of MPs [2], including the properties of the MPs (structure, size, and shape), the materials used for the formation of the photocatalyst (doping element and content), and primarily environmental factors such as humidity, temperature, light intensity, and wavelength.

Titanium dioxide (TiO_2) is a well-known photocatalyst with significant photocatalytic activity. Its photocatalytic properties are primarily attributed to its wide bandgap energy, high chemical stability, non-toxicity, and abundance. When exposed to ultraviolet (UV) light, TiO_2 can initiate a series of photochemical reactions due to its ability to generate electron-hole pairs.

The photocatalytic reaction initiates when light irradiation promotes the electron from the VB to the vacant CB. The incident photon possesses energy equal to or greater than the bandgap of TiO_2. This excitation results in the generation of holes (h^+) in the VB. The overall reaction under light irradiation can be summarized by Equation (1) [3]. When a hole in the VB encounters a water molecule, it undergoes a reaction that yields hydroxyl radicals ($\bullet OH$), as shown in Equation (2). The hydroxyl radical ($\bullet OH$) is a potent oxidizing agent and holds significant importance in photooxidation processes [4][5].

$$TiO2 \rightarrow hvh+VB+e-CB \quad (1)$$

$$h+VB+H2O \rightarrow \bullet OH+H+ \quad (2)$$

$$O2+e-CB \rightarrow O\bullet-2 \quad (3)$$

$$O\cdot-2+H+ \rightarrow HOO\bullet \quad (4)$$

$$2HOO\bullet \rightarrow O2+H2O2 \quad (5)$$

$$H2O2 \rightarrow 2OH\bullet \quad (6)$$

The hydroxyl radical ($\bullet OH$) generated by the photocatalyst exhibits non-selective reactivity towards adsorbed contaminants that are attached or in close proximity to the surface of the photocatalyst. This reactivity results in the mineralization of the contaminants. TiO_2 is particularly effective in the photodegradation of organic pollutants, both under UV and visible light irradiation.

The photoexcited electron in the CB engages in a reaction with an oxygen molecule, resulting in the formation of superoxide radicals ($O_2^{\bullet-}$) as described by Equation (3). These $O_2^{\bullet-}$ radicals actively participate in oxidation reactions while also preventing the recombination of photogenerated electron-hole pairs. This process helps maintain the electron neutrality within the semiconductor [6]. The generated $O_2^{\bullet-}$ radical undergoes protonation to form hydroperoxyl radical ($HO_2\bullet$), as depicted in Equation (4). The hydroperoxyl radical ($HO_2\bullet$) then reacts to produce hydrogen peroxide (H_2O_2) according to Equation (5). Subsequently, H_2O_2 dissociates to yield $\bullet OH$ radicals, as shown in Equation (6). To facilitate comprehension, the overall reaction to plastic degradation is illustrated through the following Equations (7)–(9).

$$h+VB+MPs \rightarrow \text{oxidize products} \quad (7)$$

$$\bullet OH+MPs \rightarrow CO_2+H_2O \quad (8)$$

$$e-+MPs \rightarrow \text{reduced products} \quad (9)$$

Under visible light, there is also a certain degree of direct degradation of MPs by TiO_2. This process involves the excitation of MPs from their ground state to an excited state upon the incidence of visible light photons. In this excited state, the plastics generate semi-oxidized cation radicals through the injection of electrons into the CB of the catalyst. The trapped electrons then react with dissolved oxygen, resulting in the formation of $O_2^{\bullet-}$. These $O_2^{\bullet-}$ radicals subsequently give rise to $\bullet OH$ radicals, which are responsible for the decomposition of the target pollutants. The indirect mechanism of plastic degradation prevails over the direct mechanism, with plastic decomposition being more prominent than the reaction induced by visible light. Furthermore, the reactions initiated by visible light are considerably slower compared to those triggered by UV light.

The $OH\bullet$ and $O_2^{\bullet-}$ radicals produced additionally initiate degradation at vulnerable points along the long polymeric chains of low-density polyethylene (LDPE), resulting in the formation of low molecular weight polyethylene alkyl radicals ($(\text{-CH}_2\text{-CH}\bullet\text{-})n$). Moreover, it has been demonstrated that the photogenerated hole (h^+) can react with organic compounds, leading to the formation of organic free radicals [7].

On the other hand, Photodegradation (in the absence of a catalyst) plays a crucial role in the breakdown of polymers [8]. When it comes to microplastics (MPs), prolonged exposure to sunlight, particularly UV light, can lead to the generation of environmentally free radicals, oxygen addition, hydrogen abstraction, and the breaking or linking of chemical chains [9]. This process can also result in morphological changes such as flaking and cracking [10], with UV light being identified as the primary influencing factor. However, the natural photodegradation of MPs is difficult to control. Song et al. [11] have observed the formation of oxygen-containing groups and cracks on the surfaces of MPs during laboratory-accelerated photodegradation. Nevertheless, there is limited information on the impact of reactive oxygen species (ROS) on the aging process of MPs due to their relatively low concentration in aquatic environments. Moreover, the photodecomposition of MPs is slow in the wild, especially in aquatic locations. Zhu et al. [12] investigated the aging of PS as a model in an aquatic environment under simulated sunlight for up to 150 days. They discovered the presence of ROS in the PS suspension due to light exposure. The study shed light on the mechanism of ROS formation and photodegradation of MPs under simulated sunlight. However, the study did not examine the extent of photoaging or the types of intermediate products in this photochemical system. Additionally, long-term exposure to simulated light irradiation can lead to excessive energy consumption or even light pollution.

2. Bare TiO_2

Kaewkam et al. [7] studied the UV-assisted TiO_2 photocatalytic degradation of virgin LDPE films, investigating the effect of UV-A (longest wavelengths = 352 nm), UV-C (shortest wavelengths = 254 nm), and TiO_2. The combination of UV radiation and TiO_2 photocatalysis was found to significantly enhance the degradation of virgin LDPE films compared to degradation under UV radiation alone or TiO_2 photocatalysis alone. TiO_2 fired at 450 °C (anatase + rutile) was photo-catalytically more active than TiO_2 (rutile-900 °C) when exposed to UV-A. The UV-assisted TiO_2 photocatalysis showed the highest degradation efficiency among the tested conditions. It was also found that TiO_2 (rutile) excited by UV-C was more suitable for the photodegradation of LDPE than TiO_2 (anatase + rutile) excited by UV-C. The photodegradation of LPDE, in the absence of TiO_2, was also studied by exposing the LDPE films to UV-A and UV-C radiations for 3, 5, 7, and 9 days. UV-C radiation resulted in faster degradation of LDPE films compared to UV-A radiation due to its higher energy, which facilitated the breakage of C-H bonds in LDPE. The ambient temperatures of the UV-A and UV-C systems were within the ranges of 30.3–32.7 °C and 36.5–38.6 °C, respectively. The increase in temperature caused by UV light irradiation was considered to have a minimal effect on the degradation of LDPE films.

Nabi et al. [13] studied the photocatalytic degradation of MPs (PS and PE) using TiO_2 films under UV irradiation, and the influence of PS sphere size and catalyst preparation was evaluated. The authors prepared three types of TiO_2 films (from TiO_2 P25) with different physicochemical properties by varying the synthesis solvent: water (WT), ethanol (ET), and Triton X-100 (TXT).

The catalytic performance of the three prepared TiO_2 films in the degradation of PS-MPs was evaluated under 12 h of UV light radiation at 254 nm. Degradation percentages of 98.4%, 91.04%, and 69.25% were obtained for the TXT, ET, and WT films, respectively. The same study was conducted only on fluorinated-tin oxide (FTO) (direct photolysis, without a catalyst), resulting in an 8.01% degradation. The superior performance of TXT-TiO_2 can be attributed to its lower band energy and efficient charge separation, which were further investigated in detail. As a result, TXT generates a higher number of electron-hole pairs under light irradiation and prolongs the charge separation, leading to significant photoactivity in PS removal. On the other hand, the underwhelming performance of the WT film is likely due to its larger particle size, lower surface area, and limited charge separation ability. The enhanced activity of the TXT film can also be attributed to its surface hydrophilicity and film texture. Surface hydrophilicity promotes the interaction between semiconductors and plastic, particles that improve the film texture, leading to charge transfer and separation that results in the fast degradation of microplastics.

The catalytic performance of the TXT-TiO_2 catalyst was evaluated by varying the size of PS-MP particles, with sizes of 700, 1000, and 5000 nm. Degradation efficiency values of 93.49%, 95.30%, and 99% were obtained, respectively, under 24 h of UV light radiation at 254 nm. This catalyst was also tested in the degradation of PE-MPs, achieving 100% efficiency after 36 h of UV light radiation at 354 nm.

It is important to highlight that the results obtained by Nabi et al. [13], were conducted in the solid phase under ambient air conditions, where a solution of PS spheres (20 µL) was deposited onto the catalyst film as well as onto the clean FTO (without catalyst) and dried at room temperature.

The degradation assay was also carried out in the liquid phase, where 0.05 g of the TXT-TiO_2 catalyst was added to a 100 mL solution of PS. A solution of 100 µL of PS (5 µm size) in 100 mL of deionized water was prepared. The solution was continuously stirred during the degradation reaction under 254 nm UV light irradiation, and samples were taken at regular time intervals. The film fabrication process does not involve the use of costly, toxic, or hazardous chemicals, making it highly efficient, beneficial, and economically important. Furthermore, the solid phase photodegradation of microplastics eliminates the release of potentially toxic intermediates into water, unlike liquid phase technologies.

Fadli et al. [14] studied the degradation of PE-MPs using TiO_2 (P25) catalysts. The degradation test was done by adding PE-MPs scrub-sized 100–150 into distilled water. For the test, 100 mL of distilled water and 50 mg of microplastics were added to a beaker glass, and then 50 mg of catalysts were added to the solution. The solution was stirred continuously during the degradation test. The tests were carried out at room temperature with the help of UV irradiation. Tests were conducted for 1, 2, 3, and 4 h with the same initial amount of MP pollutant. The degradation efficiency increased over time, reaching 56% after 4 h of reaction. The same test was conducted in the absence of a catalyst (direct photolysis), resulting in 100% recovery of the microplastics (0% degradation).

3. Modified TiO_2

Fadli et al. [14] also studied the catalytic performance of 3%Ag-TiO_2 and 3%Ag-TiO_2-1%RGO (reduced graphene oxide) catalysts in the degradation of PE. After 4 h of analysis, the degradation efficiency was 68, and 76%, respectively. The improvement in performance compared to that obtained with bare TiO_2 could be associated with the high electron mobility properties of silver metal and RGO, which act as efficient electron acceptors and increase induced photon transfer, thereby inhibiting the rate of electron-hole recombination. Additionally, silver metal exhibits strong absorption of UV and visible light, and its higher absorbance of visible light enhances the electron-hole charge separation of the photocatalyst. This results in the creation of more active sites on the catalyst's surface. Furthermore, RGO possesses a large theoretical specific surface area, which enhances electron mobility to RGO and allows for electron storage on its surface. The large surface area also improves the catalyst's adsorption capacity, facilitating contact between the catalyst and the pollutant.

Maulana et al. [15] synthesized Ag/TiO_2 nano-composites using the Photo Assisted Deposition (PAD) method. The objective of their research was to investigate the capability of these nano-composites to degrade PE-MPs present in water, specifically by examining the impact of varying particle sizes of microplastics as pollutants in drinking water. The PE-MPs degradation test was performed using the mass loss method. The effectiveness of catalysts in microplastic degradation can be determined by measuring the reduction in microplastic mass before and after subjecting them to a 2 h UV irradiation treatment. The MP particles used varied in size, specifically ranging from 100–125, 125–150, and 150–250 µm, with an initial concentration of 100 ppm. During the degradation process, magnetic stirrers were employed at a rotational speed of 2000 rpm, along with UV lamp irradiation. The addition of the Ag dopant had a positive impact on microplastic degradation, resulting in a 100% degradation rate within 120 min of irradiation. Among the different particle sizes, the best percentage of degradation was achieved with the 125–150 micrometer size, where 100% degradation was attained after 90 min of irradiation.

Zhou et al. [16] studied the potential of utilizing a TiO_2 catalyst in a photocatalytic degradation process to demonstrate the feasibility of MPs. The assays were carried out in a three-electrode quartz cell, and a 0.5 M Na_2SO_4 electrolyte solution was used. An Ag/AgCl electrode served as the reference electrode, and a Pt wire was employed as the counter electrode. N-TiO2 and Pt/N-TiO_2-1.5% were utilized as the photoanodes. The photoanode was prepared through a physical coating process. 5 mg of photocatalyst was dispersed using ultrasound in a mixture consisting of 20 µL of 1-naphthol and 500 mL of ethanol. This mixture was evenly coated onto the FTO glass substrate and subsequently dried at 60 °C for 24 h. They achieved a 29% degradation efficiency. The result showed that inducing an initial rough appearance by hydrothermal treatment was a positive factor affecting the photocatalytic degradation of PET.

Therefore, the performance of TiO_2 and modified TiO_2 photocatalysts for microplastic oxidation is influenced by various parameters. These include the type of photocatalyst material, dosage of photocatalyst, microplastic concentration, light source and intensity, particle size and morphology, and surface modifications. The choice of photocatalyst material, such as TiO_2 or modified TiO_2, affects its activity and stability. Particle size and morphology affect the active surface area and mass transfer. Surface modifications, like doping or coatings, can improve the photocatalyst's absorption properties and introduce catalytic sites, enhancing oxidation efficiency.

4. Bare ZnO

Tofa et al. [17] tested the degradation of fragmented, low-density polyethylene (LDPE) MP residues by visible light-induced heterogeneous photocatalysis activated by ZnO nanorods (NRs). In an experimental setup, photocatalytic degradation of a 1 cm × 1 cm LDPE film was conducted for a duration of 175 h. The experiment took place in a petri dish containing deionized water and the photocatalyst. Visible light illumination was provided using a 50 W dichroic halogen lamp in an ambient air environment. The photocatalytic oxidation of LDPE resulted in the generation of low molecular weight compounds, including hydroperoxides, peroxides, carbonyl groups, and unsaturated groups. This led to an increase in the brittleness of the LDPE material, accompanied by the formation of wrinkles, cracks, and cavities on its surface. The evolution of carbonyl and vinyl groups are used as indicators for monitoring the degree of degradation of a polymer. Three catalysts with different surface areas were tested, and carbonyl and vinyl indices (CI and VI) showed that the photocatalytic performance improved with the catalyst surface area.

The relationship between the carbonyl index (CI) and vinyl index (VI) with microplastics degradation can provide insights into the extent and progress of the degradation process. Both CI and VI are indicators of chemical changes occurring during degradation and can be used to assess the degradation level of microplastics. The carbonyl index (CI) is a measure of the carbonyl functional groups formed during degradation. These functional groups, such as aldehydes and ketones, are typically generated due to oxidation reactions. The increase in CI value indicates a higher concentration of carbonyl groups, suggesting a higher degree of degradation. On the other hand, the vinyl index (VI) reflects the degree of unsaturation within the microplastic polymer chain. As degradation occurs, the polymer chain undergoes cleavage and breaks into smaller fragments. This process can lead to the formation of unsaturated bonds, resulting in an increase in the VI value.

Based on the findings, a degradation pathway for LDPE film was proposed. The process begins with the generation of hydroxyl and superoxide radicals from the catalyst. These radicals initiate degradation at vulnerable points in the long polymeric chains, such as chromophore groups and defects. This leads to the formation of low molecular weight polyethylene alkyl radicals, followed by chain breaking, branching, crosslinking, and oxidation of LDPE. Subsequently, peroxy radicals are formed as oxygen is incorporated into the system. These radicals then abstract hydrogen atoms from the polymeric chains, resulting in the formation of hydroperoxide groups. The hydroperoxide groups are significant oxygenated products that govern the rate of photocatalytic degradation. Their dissociation produces alkoxy radicals, which undergo further reactions to generate species containing carbonyl and vinyl groups. These groups contribute to chain cleavage.

The presence of carbonyl and vinyl groups confirms the photo-oxidative degradation of LDPE films in the presence of catalysts. The degradation process ultimately leads to the generation of volatile organic compounds, such as ethane and formaldehyde.

Sun et al. [18] studied the degradation of MPs using ZnO nanoparticle NPs as photocatalysts. Both MPs and ZnO NPs were extracted from a commercial sunscreen. They found that a short exposure duration of 12 h under simulated sunlight did not lead to surface oxidation of MPs. However, when ZnO nanoparticles (NPs) were added, surface oxidation of regular microplastics (MPs) was observed. The presence of ZnO NPs and water did not significantly induce surface oxidation. However, when sunlight was involved, a time-dependent increase in oxidation was observed. With the presence of sunlight, water, and ZnO NPs, the authors demonstrated the photooxidation of MPs by the produced hydroxyl radicals, which promoted the fragmentation of MPs. Spherical MPs were fragmented into smaller pieces with sharper edges, suggesting that primary MPs were transformed into secondary MPs, which were more likely to present on human skin.

Razali et al. [19] studied the impact of the UV-assisted thermo-photocatalytic reaction on the degradation of polypropylene (PP) macro- and microplastics in a water-based environment over a period of 6 h. Zinc oxide (ZnO) nanoparticles, with a size below 50 nm, were utilized as the photocatalyst in the experiment. The degradation rate of both macro and microplastics made of polypropylene (PP) suspended in water has been significantly influenced by the UV-assisted thermo-photocatalytic reaction using zinc oxide (ZnO) as the catalyst.

Under the influence of UV light, ZnO photocatalyst generates reactive radical species, such as superoxides or hydroxyl radicals, which are highly oxidizing. These radicals swiftly attack and oxidize the polar functional groups present in PP, leading to its degradation. The rate of photodegradation of PP is further enhanced by increasing the reaction temperature, particularly at around 50 °C. This temperature elevation promotes the fragmentation of both macro and microplastics.

Statistical analysis confirmed that the reaction temperature and size of the PP plastic, as well as the interaction between these variables, are important factors to consider. However, the dosage of ZnO catalyst had minimal impact on the degradation of PP plastic.

5. Modified ZnO

Tan et al. [11] studied the applicability of photocatalysis in degrading LDPE microplastics by using graphene oxide/zinc oxide (GO-ZnO) photocatalysts under UV light irradiation. The interaction between pH, temperature, and catalyst loading on the mass loss of LDPE was investigated. Optimal conditions for microplastic mass loss (39.28%) were determined at a pH of 9.81, a temperature of 30 °C, and a catalyst loading of 1500 ppm.

Tofa et al. [20] studied the degradation of fragmented microplastics particularly low-density polyethylene (LDPE) film in water, through visible light-induced plasmonic photocatalysts comprising of platinum nanoparticles deposited on zinc oxide (ZnO) nanorods (ZnO-Pt). The introduction of plasmonic metal in modified ZnO-Pt catalysts resulted in approximately a 13% increase in the oxidation potential of LDPE film compared to the ZnO nanorods in their original state. This suggests that incorporating plasmonic metal into ZnO could offer a promising approach to accelerate the oxidation of microplastic pollutants in water using sunlight. Authors found that the incorporation of platinum nanoparticles in the catalyst leads to an improvement in the absorption of visible light, thanks to the plasmon absorption phenomenon. Furthermore, the diffusion of photogenerated electrons from the ZnO nanorod interfaces into the platinum nanoparticles helps to minimize electron-hole recombination. The presence of platinum nanoparticles on ZnO nanorods clearly enhances the efficiency of photodegradation. The carbonyl index and vinyl index experienced a notable increase of 13% and 15%, respectively. These findings strongly indicate that the degradation efficiency of ZnO-Pt plasmonic photocatalysts is significantly improved compared to unmodified ZnO nanorods.

6. Other Photocatalysts

The utilization of photocatalysts beyond TiO_2 and ZnO has emerged as a promising alternative for the removal of microplastics present in water. Materials such as graphene, tungsten oxide (WO_3), and molybdenum dioxide (MoO_2) have been investigated for photocatalytic degradation of microplastics. These alternative photocatalysts offer distinct properties and characteristics that can enhance the removal efficiency of microplastics compared to traditional ones. Furthermore, the combination of different photocatalysts in hybrid systems has shown promising potential in efficiently degrading microplastics. These advancements open up new possibilities in the development of photocatalytic technologies to address the issue of microplastics in water.

Jian et al. [21] employed an ultrathin BiOCl (BiOCl-X) material with a high hydroxy content, prepared under room temperature conditions for the photocatalytic degradation of MPs. X represents the load of mannitol added. The researchers investigated its effectiveness in the photocatalytic degradation of microplastics (MPs). Remarkably, BiOCl-X exhibited significant potential for degrading MPs through photocatalysis, surpassing the performance of BiOCl nanosheets. The mass loss of plastics achieved using BiOCl-X was found to be 24 times greater compared to the degradation achieved with BiOCl nanosheets. Furthermore, the study revealed that smaller microplastics degraded faster, while light-colored or stable microplastics experienced a significant reduction in photocatalytic degradation. Additionally, the degradation of microplastics was found to be more pronounced in acidic conditions, whereas the Coulomb repulsion in alkaline solutions protected them from degradation.

Khairudin et al. [22] proposed a promising method of degrading the 1.1 μm polystyrene latex (PSL) beads MPs using a self-propelled and magnetically recovered BiOI-Fe_3O_4 microswimmer. The findings demonstrate the effective degradation of 64% of polystyrene MPs within 120 h using flake-like BiOI-Fe_3O_4 microswimmers. These microswimmers significantly reduce the concentration of MPs in an aqueous solution from 0.05 g/L to 0.018 g/L. The movement of the microswimmers is induced by the presence of visible light and H_2O_2 fuel, which decomposes into oxygen bubbles. Observations reveal that the microswimmers, with an average particle size of 3.913 μm, can achieve a reasonable speed of 3.0498 μm/s under 3.6 W visible light irradiation and a 5 wt% H_2O_2 concentration. Moreover, it is evident that PSL-MPs degrade rapidly when exposed to visible light for less than 24 h. The degradation of PSL through photocatalytic processes was investigated under visible light irradiation for 24 h, comparing the absence of a photocatalyst with the presence of pristine Fe_3O_4, pristine BiOI, and a composite BiOI-Fe_3O_4 microswimmer. There was no significant degradation of PSL (~1%) in the absence of a photocatalyst after 24 h of light exposure. In the presence of mesoporous Fe_3O_4 with a high surface area of 63.0857 m^2/g, a 12% degradation of PSL was observed. The low percentage removal of PSL can be attributed to the high band gap energy (3.2 eV) of the synthesized Fe_3O_4, requiring more photon energy to facilitate electron transfer from the valence band to the conduction band, resulting in reduced degradation performance. However, when the composite BiOI-Fe_3O_4 microswimmer was present, a 56% degradation of PSL was achieved under visible light irradiation, surpassing the performance of the pristine BiOI microswimmer, which achieved 38 degradation under the same illumination period of 24 h. The improved degradation performance of the composite microswimmer can be attributed to the mesoporous structure, which slightly increases the specific surface area and the number of surface-active sites.

Olajire et al. [23] studied the photocatalytic potential of Au NPs through the solid-phase degradation of low-density polyethylene (LDPE) film. The photoinduced degradation of LDPE@Au nanocomposite film was higher than that of the pure LDPE film. The weight loss of LDPE@Au (1.0 wt%) nanocomposite film steadily increased and reached 51.4% in 240 h under solar light irradiation, compared to the photo-induced LDPE with only 8.6 ± 0.7%. However, LDPE film with 1.0% Au NPs gave a weight loss value of 4.72 ± 0.71 under the dark condition at the end of 240 h. Thus, LDPE film with 1.0% Au NPs showed a degradation efficiency of 90.8% under solar irradiation after 240 h. The reusability of the nanoparticles in the photocatalytic degradation reaction up to five consecutive cycles without substantial loss in its catalytic performance confirmed the sustainability of the system.

It is important to highlight that the efficiency of removing microplastics from water is influenced by the functional groups present in the materials used. For example, the polarity of microplastics and organosilanes has been found to have a strong effect on removal efficiency [24]. The alkyl group in alkyltrichlorosilanes also plays a major role in the agglomeration and fixation of microplastics, with intermediate chain lengths between 3 and 5 carbon atoms being the most suitable [25]. Various factors, such as coagulant type and dose, microplastic material, shape, and size, as well as water quality, can also impact the removal efficiency of microplastics in drinking water treatment processes [26]. The combination of separation and degradation processes has shown promising results in achieving high removal efficiency for microplastics and nanoplastics in water [27]. Additionally, optimizing treatment conditions and exploring emerging technologies such as sol-gel technology can further enhance the removal efficiency of microplastics in water treatment [28].

In conclusion, these studies provide valuable insights into the photocatalytic degradation of microplastics using various photocatalysts. The investigations shed light on the degradation mechanisms, optimization of reaction conditions, and potential impacts on human health. The findings contribute to the development of photocatalytic technologies to mitigate the environmental impact of microplastics in water systems. However, further research is needed to explore the long-term performance, scalability, and real-world applicability of these photocatalysts for effective microplastic removal. In this regard, considering the results presented in this section and other unreported studies, it can be said that the photocatalytic degradation efficiency of MPs (Microplastics) present in water is mainly affected by factors stemming not only from the photocatalyst but also from the properties of the MP itself and the reaction conditions in which it takes place.

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